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Modern analysis of surface irrigation systems with WinSRFR

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ABSTRACT

WinSRFR is a new generation of software for analyzing surface irrigation systems. Founded on an unsteady flow hydraulic model, the software integrates event analysis, design, and operational analysis functionalities, in addition to simulation. This paper provides an overview of functionalities, interface, and architectural elements of the software, and discusses technical enhancements in version 2.1, released in late 2007, and version 3.1, scheduled for release in 2009.

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1. Introduction

Since the late 1970s, The USDA-Agricultural Research Service has been involved in the development of hydraulic simulation models and related software tools for analyzing surface irrigation systems. Key results of this development are the simulation program SRFR (Strelkoff et al., 1998), the design tool for sloping, open-ended border strip systems BORDER (Strelkoff et al., 1996), and the design tool for level-basin systems BASIN (Clemmens et al., 1995). A new generation of surface irrigation software, named WinSRFR, has been under development since 2004. An initial objective of the WinSRFR development project was to convert the DOS-based SRFR, BORDER, and BASIN programs into an application for the Windows operating system. In the long-term, the objectives are to develop a tool for conducting practical analyses on different types of surface irrigation systems, and to develop a new software foundation for continued research in surface irrigation hydraulics. The purpose of this article is to provide an overview of the WinSRFR software package, describe its functionality and organization, and discuss surface irrigation analytical procedures that are being incorporated into the software. These enhancements are driven by the need to provide close integration among analytical components. The article also discusses future development plans. A companion article presents a detailed example to illustrate capabilities of the software.

2. Program functionality and organization

2.1. WinSRFR Worlds

The functionality and organization of WinSRFR were defined based on the analytical process typically followed in assessing and improving the hydraulic performance of surface irrigation systems. Program functionalities, referred to as WinSRFR Worlds, are Event Analysis, Operation Analysis, Physical Design, and Simulation.

The first step in the analytical process is an evaluation of current performance based on field-measured data. Hence, the Event Analysis World provides tools for summarizing, graphing, and analyzing field evaluation data. The primary purpose of the evaluation is to describe the disposition of the applied water, but can also be used to estimate infiltration and/or hydraulic roughness characteristics of a field, which are key inputs for subsequent analyses. At this time, WinSRFR provides three evaluation procedures: (a) a post-irrigation volume balance based on a measured infiltration profile (which requires probe penetration data, water holding characteristics of the probed soil profile, and estimates of soil water content); (b) a post-irrigation volume balance based on advance and recession measurements (Merriam and Keller, 1978; USDA-NRCS, 1997), and; (c) an advance-phase volume balance based on Elliott and Walker's two-point method (Elliott and Walker, 1982). The last two procedures calculate infiltration parameter estimates; some details of the implementation of these procedures will be discussed later.

The second step in the analytical process is to examine alternative operational strategies with the given system. The Operations World is used to analyze the performance tradeoffs among different combinations of flow rate and cutoff time for a

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system of known dimensions, slope, and soil characteristics. The analysis is conducted with the help of performance contours, which depict the variation of irrigation performance measures as a function of the decision variables. Performance measures (Burt et al., 1997) analyzed by WinSRFR include distribution uniformity, potential application efficiency, runoff and deep percolation fractions, minimum infiltrated depth, total applied depth, the ratio of advance distance at cutoff time relative to field length (for cases where cutoff precedes advance to the end of the field), or the ratio of cutoff time to final advance time (for cases where cutoff follows completion of advance). These tools allow the user to search for combinations of the decision variables that will result in high levels of uniformity and efficiency while taking into account practical and hydraulic constraints. For example, when selecting a discharge-cutoff time combination, the user needs to account for the maximum available flow rate and the duration of irrigation set times relative to work-shift hours. Numerous hydraulic simulations are needed to generate the performance contours for a particular irrigation system. Techniques used in WinSRFR to generate performance contours are described further below.

If the optimized operation still results in unacceptable performance, then changes to the existing design should be explored. The Design World is used to optimize the physical dimensions (length and width) of an irrigation system for given inputs. As in the Operations World, the analysis is based on performance contours as a function of the decision variables. The design also allows the user to analyze the tradeoffs between different field-length and inflow combinations, with the set width held constant. In many situations, field slope can also be considered a decision variable, and for such cases, separate design analyses are conducted for slope values of interest. As in operational analysis, the design process aims to maximize performance subject to the maximum flow rate available, maximum and minimum field dimensions, and other hydraulic considerations.

Sensitivity analyses can be conducted with unsteady flow simulation to assess the impact of variations from the assumed design conditions in infiltration and roughness characteristics, inflow rate, bottom slope non-uniformities, etc. Operational and design recommendations can then be fine-tuned to assure reasonable levels of performance under the expected range of field conditions. To this end, the Simulation World provides access to the SRFR simulation engine (Strelkoff et al., 1998). Data developed in the Operations, Design, and Event Analysis Worlds can be copied into the Simulation World to create simulation scenarios; alternatively, the user can enter data manually. In addition, the SRFR engine provides simulation services to the Event Analysis, Operations, and Design Worlds. For example, simulation is used to validate parameter estimates computed in the Event Analysis World. At this time, sensitivity analyses are conducted manually, by creating multiple scenarios in the Simulation World.

2.2. Data structures and user interface elements

Data structures and program interface elements are defined by the functionalities of the software. A WinSRFR project consists of folders for Event Analysis, Operation Analysis, Design Analysis, and Simulation scenarios. A project file typically is associated with a particular farm, but can simply represent a collection of related hypothetical scenarios. Each project ("Farm") consists of at least one case ("Field") folder. In turn, each case folder contains one or more function folders (Events, Operations, Design, and Simulation). Function folders hold one or more field scenarios. These various folders are accessed though the Analysis Explorer, located on the left side of the main screen (Fig. 1). This tree control structure and associated interface elements provide great flexibility in organizing and documenting the data.

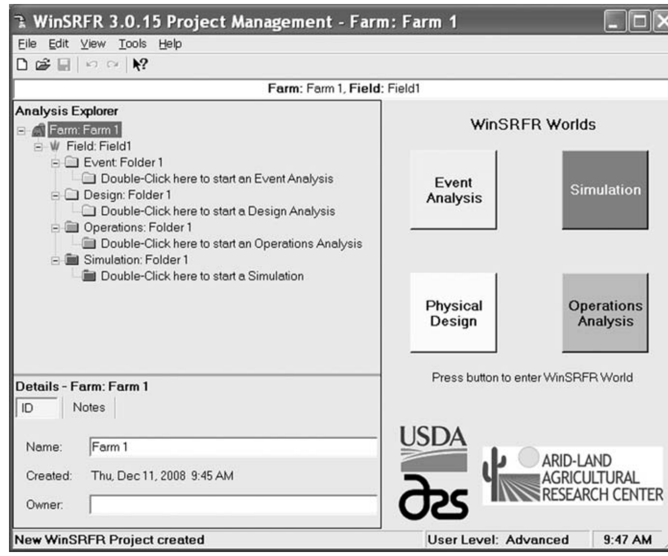

Fig. 1. WinSRFR main screen.

A particular scenario in a given World is represented by a tabbed Window, from which the user can edit data, run the analysis, and view outputs. For example, Fig. 2 depicts the main tab in the Physical Design World. Tabbed Windows for the different Worlds have similar features and organization. The first tab defines fundamental physical options. Selecting an option configures the user interface to display dialog boxes specific to the desired type of analysis.

Input data and results from an event analysis will often be needed as inputs for a simulation, operation, or design study. The needed data exchange is accomplished through the Explorer tree (see the WinSRFR main screen, Fig. 1), by copying and pasting a selected Event Analysis scenario into a Simulation, Operation Analysis or Design folder. WinSRFR sorts out the data pertinent to the receiving world for display in that world. This transfers the inputs provided to the evaluation as well as the infiltration parameter estimates needed for simulation, operations analysis, or design. Similarly, a selected operational or design solution can be transferred to the Simulation World using the same mechanism, with Operations or Design Worlds outputs copied into the Simulation World as inputs.

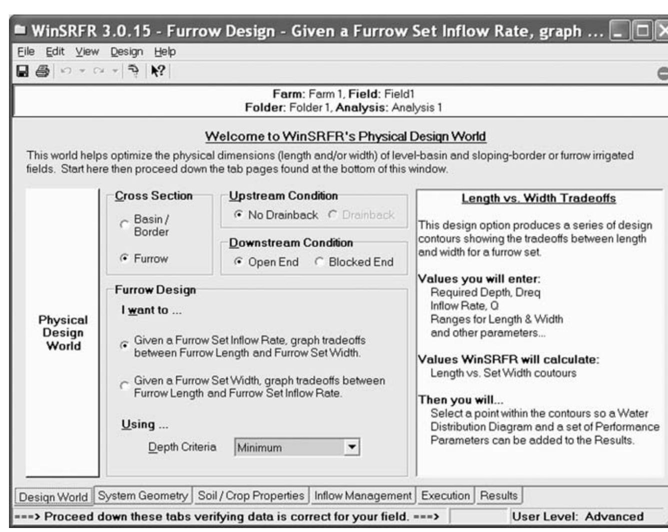

Fig. 2. WinSRFR Design World: main tab.

3. Technical enhancements relative to the legacy software and WinSRFR 1.2

Development of a tool that integrates various types of analyses on different types of surface irrigation systems is complicated by at least two factors, the underlying simulation model, and differences in assumptions and analytical procedures employed by different worlds.

The governing equations of the simulation engine impose a fundamental limitation on the ability of the software to deal with different system types. Because those equations assume one-dimensional flow, system properties are allowed to vary along the length of the field, or with time, but not across its width. Hence, the analysis is limited to single borders or basins with no cross-slope and to individual furrows. Since furrows are managed as a set and not individually, WinSRFR allows users to specify a set inflow and calculates some of the results for furrow sets. However, all underlying calculations are for a single unit and, therefore, assume identical furrows within the set. While cross-slopes cannot be simulated by the engine, it is possible to approximately model some two-dimensional flow problems. For example, borders and basins that are cut off on a slant because of the irregular shape of a field can be modeled on the basis of average length. Within the one-dimensional flow limitation, the simulation engine provides numerous options for configuring the bottom slope, cross-sectional geometry, roughness and infiltration characteristics, and inflow rate.

The ability of the software to conduct different types of analyses on a given irrigation system rests on the extensive communication between the Worlds, especially since the software uses outputs from one World as input to another. A key challenge to achieving this integration is that while SRFR provides numerous options for defining system properties for simulation, existing procedures for evaluation or design and operations analyses support only some of those configuration options. The goal then is to make the options offered by various Worlds more compatible with each other. The following sections discuss two particular areas that received special attention to provide greater integration in WinSRFR V. 2.1 and 3.1. One deals with formulations for computing infiltration in the simulation engine, contrasted with corresponding parameter-estimation procedures provided in the Event Analysis World. The second is an exposition of design and operations analysis procedures in furrows, not available in the initial release.

3.1. Infiltration computations

WinSRFR presently uses empirical formulas for infiltration computations. In a one-dimensional view of the irrigation stream, in which all variables are functions of distance and time only, the pertinent infiltration variable is the volume infiltrated per unit length $A_z(x, t)$ $[L^3/L]$. The simulation engine calculates A_z as

$$A_z = WP \cdot z \tag{1}$$

In which WP $[L]$ is the transverse length of the soil–stream interface through which the infiltration must take place, and z is the volume infiltrated per unit area of the soil surface $[L^3/L^2]$. Eq. (1) assumes water infiltrates in a direction normal to the soil surface. This is a reasonable assumption when dealing with border strips and basins, where water infiltrates essentially in the vertically direction and WP is constant and equal to the border/basin width W. Eq. (1) represents furrow infiltration less adequately because of the contribution of horizontal flow to total infiltration, and because WP varies with distance and time as the depth of the stream rises and falls with the passage of the stream. Options for calculating z and WP are discussed next, along with the uses and limitations of these options.

3.1.1. Infiltration functions

Table 1 lists the options provided by WinSRFR for calculating z. In these expressions, the exponent a is dimensionless, and k, b, and c are parameters with dimensions and units consistent with those of z and τ.

The Kostiakov (1932) equation (Eq. (2)) has been widely used in irrigation studies but it can represent the process inaccurately in soils with a well-defined steady-state infiltration rate. Mezencev (1948) recognized this limitation and added to Eq. (2) the product $b\tau$, with b the long-term infiltration rate. That equation, commonly identified in the literature as the Modified Kostiakov equation, was further modified in the SRFR program (Strelkoff et al., 1998), by adding a constant c to account for instantaneous macropore infiltration (Eq. (3)). The USDA-Natural Resource Conservation Service (NRCS) (formerly Soil Conservation Service, SCS) proposed the use of the infiltration family concept as a way of categorizing infiltration behavior for different soils (USDA-SCS, 1974; USDA-SCS, 1984). The corresponding infiltration equation is given by Eq. (4), in which k and a are specific to each family but c is constant for all families. Because of the similarity between the infiltration families presented in the 1974 and 1984 publications, WinSRFR combines those families as a single set. While a new set of NRCS infiltration families has been recently proposed (Walker et al., 2006), those families have not been adopted for the current release of the program but may be adopted in a future release. The characteristic-time concept is based on the premise that infiltration can be characterized by the time needed to infiltrate the target depth. When using this concept, the *characteristic* time, target depth, and an exponent for Eq. (2) (gleaned from previous experience with soils in the area) need to be specified; the

Table 1
WinSRFR options for the calculation of infiltrated depth.

Name	Equation form	Equation
Kostiakov formula (Kostiakov, 1932; Lewis, 1937)	$z = k\tau^a$	(2)
Modified Kostiakov formula (Mezencev, 1948; Strelkoff et al., 1998)	$z = k\tau^a + b\tau + c$	(3)
NRCS infiltration family (USDA-SCS, 1974; USDA-SCS, 1984)	$z = k\tau^a + c$	(4)
Known characteristic infiltration time (Strelkoff et al., 1998)	$z = k\tau^a$	(2)
Time-Rated intake family (Merriam and Clemmens, 1985)	$z = k\tau^a$ with a given by	(2)
	$a = 0.675 - 0.2125\log_{10}(\tau_{100})$	(5)
Branch function (Clemmens, 1981)	$z = k\tau^a + c, \quad \tau \le \tau_b$ $z = k\tau_b^a + c + b\cdot(\tau - \tau_b), \quad \tau > \tau_b$ $\tau_b = \left(\frac{ak}{b}\right)^{1/(1-a)}$	(6)

parameter k can be found then from Eq. (2). The Merriam and Clemmens' (1985) Time-Rated families are based on the same concept, but enhanced by an empirical study that related the time to infiltrate a target depth of 100 mm, τ_{100}, to the exponent a. The relationship is presented as Eq. (5), in which τ_{100} is expressed in hours. The branch function (Clemmens, 1981) models a discontinuous infiltration rate, in which steady-state is achieved suddenly following an initial period in which infiltrate rate changes rapidly. In Eq. (6), τ_b is the time the function branches to the constant final infiltration rate, b.

Empirical infiltration equations have a long history of use in surface irrigation engineering analyses because they tend to fit reasonably well field-measured data. Moreover, simulation studies have shown that the behavior of different empirical equations is consistent with solutions developed from porous media flow theory (Haverkamp et al., 1988; Perea et al., 2003; Furman et al., 2006). Hence, selection of a function for a particular use does not depend on theoretical considerations but, rather, on its ability to represent the measured infiltration behavior for a time commensurate with the duration of particular irrigation event. For example, with lengthy irrigation events in which the infiltration rate approaches a steady state, one would use a formulation containing the b term.

3.1.2. Wetted perimeter effect options

WinSRFR offers four wetted perimeter choices when dealing with furrows, each of which represents a different assumption for the effect of variable flow depth on infiltration. The choice of WP option depends partly on user preference but also on the method adopted for calculating z. The relationship between z and WP will be explained later.

3.1.2.1. Furrow spacing. This simple assumption uses the furrow spacing FS as a nominal wetted perimeter. Then,

$$A_z = WP \cdot z = FS \cdot z \tag{7}$$

and the dimensions of z are volume/(unit length $\times$ *furrow spacing*). This formulation is equivalent to the approach used in other furrow-irrigation models (e.g., SIRMOD, Walker, 2003) and in the 2006 NRCS infiltration families (Walker et al., 2006) which input a formula for furrow infiltration A_z (volume per unit length) directly, rather than for z, i.e.,

$$A_z = K\tau^a + B\tau + C \tag{8}$$

In this expression the units of K, B, and C reflect the area units of A_z. For a given irrigation scenario, if infiltration function is specified in the form of Eq. (8), the parameter values can be converted to a form compatible with Eq. (3) (i.e. from uppercase to lowercase parameter values) simply by dividing by the furrow spacing.

3.1.2.2. NRCS empirical wetted perimeter. The NRCS infiltration families were originally developed from data collected in border irrigation trials [with dimensions of volume/(unit length $\times$ *unit width*)]. The agency developed a procedure to adapt the resultant one dimensional-infiltration families to infiltration in furrows through an empirical wetted perimeter WP_{NRCS} (USDA-SCS, 1984; Walker et al., 2006). This is calculated for the flow conditions (discharge Q, bottom slope S_0, and Manning roughness n) at the inlet end of the furrow but applied to the entire length of the irrigation stream. Then,

$$A_z = WP_{\mathrm{NRCS}} \cdot z_{\mathrm{NRCS}} \tag{9}$$

in which z_{NRCS} is given by Eq. (4). The formula for WP_{NRCS} is

$$WP_{\mathrm{NRCS}} = c_1 \left(\frac{Qn}{S_0^{0.5}}\right)^{0.4247} + c_2 \tag{10}$$

in which c_1 and c_2 are constants that depend on the units of Q and WP_{NRCS} (if Q is given in l/s and WP_{NRCS} in m, the constants are 0.265 and 0.227, respectively). WinSRFR interprets Q as the average discharge rate over the total period of inflow, except in cut-back scenarios in which – like in the original USDA-SCS publication – before- and after-cutback values are inserted in the formula – with consequent reductions in wetted perimeter after cutback. Likewise, the bottom slope that WinSRFR enters in the formula is the average bottom slope for the entire length of run. For zero slope cases, S_0 is replaced with the following estimate of the friction slope S_f (USDA-SCS, 1984):

$$S_f = \frac{c_3 Q^{c_4}}{L} \tag{11}$$

In Eq. (11), c_4 = 0.3419 and c_3 is a constant dependent on the units of Q and L [0.9282 m/(m^3/s)^{c4}]. The numerator of Eq. (11) is an empirical encapsulation of data on the flow depth at the furrow inlet, while L is the total furrow length.

A key feature of Eq. (10) is that the constant c_2 accounts for two distinct physical factors. One, amounting to 0.01408 m, is part of the fit of the formula to many different combinations of trapezoidal-furrow base and side slopes. The larger part, 0.213 m, reflects the observation that lateral and even upward suction in a furrow increases its infiltration over what would occur downward in a border strip of width equal to the furrow wetted perimeter. The 0.213-m constant represents an approximate, empirical fit to the data (see Strelkoff and Clemmens, 2007, for a comparison of the formula results with wetted perimeter based solely on the geometry of trapezoidal furrows).

Equation (10) was developed based on trapezoidal furrows with bottom widths between 0.06 and 0.15 m and side slopes (H/V) between 1:1 and 2:1 (USDA-SCS, 1984) and should not be used outside this range. Even within this range, wetted perimeter can vary substantially while Eq. (10) computes the same value for any combination of bottom width and side slope (Perea et al., 2003). Similarly, Eq. (11) ignores the effect of furrow geometry, and additionally of hydraulic roughness, on the hydraulic gradient. The range of application of this formula is not stated in the original USDA-SCS publication. Finally, use of Eq. (10) in combination with Eq. (11) results in a small discontinuity in the calculated wetted perimeter, when going from small slopes to a zero slope. Despite these limitations, these procedures were incorporated into the WinSRFR package because they are supported by field-measured data and continue to be used by NRCS personnel in combination with the infiltration families.

3.1.2.3. Representative upstream wetted perimeter. Two of the wetted perimeter options offered by the original SRFR engine were Upstream Wetted Perimeter at Normal Depth and Upstream Wetted Perimeter. The former option is applicable with relatively steep bottom slopes, i.e. under conditions where kinematic flow conditions can be assumed (Strelkoff and Clemmens, 1994). The latter option applies also to fields with relatively mild slope, in which upstream rises gradually. With both options, the SRFR engine updates the wetted perimeter as a function of time-variable flow $Q(t)$. These same options were incorporated into WinSRFR V. 1.1. The Representative Upstream Wetted Perimeter replaces those options. It is conceptually similar to the USDA-NRCS approach in that it assumes a constant wetted perimeter effect based on the average inflow to the furrow and the average field slope, but does not include any term to account for lateral infiltration. The expected dimensions of z are, as with Eq. (9), volume/(unit length $\times$ unit width). The method calculates the upstream flow depth y_0, which is needed to calculate the representative upstream wetted perimeter, using the following relationship (Valiantzas, 1993):

$$-\frac{\beta y_0}{L} = S_0 - \frac{Q^2 n^2}{A^2 R^{4/3}} \quad (12)$$

Eq. (12) is an approximation to the zero-inertia equation of unsteady open-channel flow,

$$\frac{\partial y}{\partial x} = S_0 - S_f \quad (13)$$

In these expressions, L is the field length, and β is a correction factor that accounts for the curvature of the water-surface profile. $\beta = 0.45$ gives reasonable upstream depth estimates under a wide range of flow conditions, except with steep slopes and short irrigation times (Bautista et al., 2008). Established geometric relationships for both trapezoidal and parabolic (power-law) furrows are used to determine A, WP, and therefore, R, the hydraulic radius. Calculations for parabolic furrows are based on the procedures described in Strelkoff and Clemmens (2000), which also points out the inconsistency in the common practice of specifying both top width and wetted perimeter as monomial power laws of depth. Eq. (12) can be applied with any non-negative value of S_0 and yields normal depth for sufficiently large values of S_0 and L. The expression was initially developed to estimate y_0 at any time during the advance phase. In that case, the average Q is substituted with the instantaneous Q and L with the stream advance distance x_A.

3.1.2.4. Local wetted perimeter. This option accounts for the unsteady rise and fall of local flow depths on infiltration, using Eq. (14):

$$\begin{aligned} A_{i,j} &= A_{i,j-1} + \delta A_{zi,j} \\ &= A_{i,j-1} + \{z(\tau_{i,j}) - z(\tau_{i,j-1})\} \times \overline{WP}_{i,j} + c(WP_{i,j} - WP_{i,j-1}) \end{aligned} \quad (14)$$

Here the increment δA_Z in the course of a time step at a particular location x_i and time t_j is the product of the increment in z [volume/(unit length $\times$ unit width)] and the current wetted perimeter, averaged over the time step. $\overline{WP}_{i,j}$ is the average wetted perimeter over the time step computed as a geometrical function of flow depth at that location and time, and the constant c term contributes to δA_Z only if $WP_{ij} > WP_{i,\,j-1}$. Use of this formula is presently limited because the parameters cannot be readily estimated by conventional volume-balance procedures, including those currently provided by WinSRFR.

3.1.3. Relationship between infiltration function and wetted perimeter

The *z-WP* combinations allowed by WinSRFR are listed in Table 2. Use of the empirical NRCS wetted perimeter is allowed only in combination with the NRCS Infiltration Families, since those concepts were developed jointly. Similar to the NRCS Families, the Time-Rated families have published coefficients and the resulting z values have dimensions of volume/(unit width $\times$ unit length). They were developed for border irrigation, but can be adapted to furrows only if adjusted on the basis of wetted perimeter, either using the representative or local wetted perimeter concepts. Because the coefficients of the Kostiakov, Modified Kostiakov, characteristic time, and Branch equations are calibrated values, they can be used in combination with any of the wetted perimeter options, except the NRCS option. This does not make the wetted perimeter option interchangeable because the coefficients of z are specific to a particular wetted perimeter option.

A logical concern is whether any of the furrow infiltration formulations provided by WinSRFR can generate realistic results under a wide range of soil and hydraulic conditions or whether a specific combination is recommended for particular conditions. Trout (1992) attempted to measure wetted perimeter infiltration effects on the field and found that changes in furrow geometry and roughness during an irrigation event mask those effects. In a more recent study, Walker and Kasilingam (2004) reached similar conclusions. These studies support the idea of calculating infiltration directly on a volume per unit length basis (i.e. on a furrow spacing basis), as has been done in many published furrow irrigation studies. Fangmeier and Ramsey (1978) measured a linear relationship between furrow wetted perimeter and infiltration in precision furrows. These results support the use of either the Representative Upstream Wetted Perimeter or NRCS options. In comparison with the furrow spacing method, both of these approaches provide a mechanism for adjusting the intake rate to inflow rate conditions different than the ones used in the estimation. In a preliminary study, Perea et al. (2003) evaluated the ability of the USDA-NRCS wetted perimeter approach (Eq. (10)), and the local wetted perimeter method (Eq. (14)) to fit infiltration predictions based on numerical solution of the Richards equation [HYDRUS-2D, Šimunek et al. (1999)]. Those comparisons disclosed that the NRCS approach eventually overestimates the theoretical predictions while the local wetted perimeter method, Eq. (14), underestimates infiltration at long times, at least for the conditions of the study. Similar comparisons are not available for the other two algorithms included in WinSRFR, but we can assume that, with properly calibrated parameters, they are also likely to mimic infiltration behavior predicted based on porous media flow theory for limited times only. These results suggest that any of the available formulations have some merit for limited times. However, the advantages of any particular formulation are difficult to establish because of infiltration variability effects, both along a furrow and from furrow-to-furrow. For example, some researchers have coupled the unsteady surface flow equations to physical infiltration models (Tabuada et al., 1995; Wohling et al., 2006). With properly calibrated parameters, those models can replicate the advance trajectory and the final mass balance of an observed irrigation event. Less clear is whether those models can predict the longitudinal distribution of infiltrated water better than simpler empirical approaches. Such predictions are complicated by spatial variations in soil properties, difficulties in characterizing initial and boundary conditions, and processes not explained by porous media flow theory. Given our current inability to characterize this variability, there seems to be little justification at this time for using other than simple approaches to characterize wetted perimeter effects in furrow infiltration.

Table 2
z-WP combinations allowed by WinSRFR for the computation of infiltration per volume length in furrows.

Infiltration formula	Furrow wetted perimeter options
Kostiakov Modified Kostiakov Branch	Furrow spacing Representative upstream wetted perimeter Local wetted perimeter
NRCS infiltration families	NRCS empirical wetted perimeter
Time-Rated infiltration families	Representative upstream wetted perimeter Local wetted perimeter
Characteristic time	Furrow spacing

3.2. Parameter estimation procedures in the Event Analysis World

As indicated earlier, WinSRFR (V. 2.1 and 3.1) incorporates two methodologies for estimating infiltration parameters from irrigation measurements, Merriam and Keller's post-irrigation volume balance (MK-PIVB) and Elliott and Walker's two-point method.

Implementation of these methods in WinSRFR is discussed next, with reference to the infiltration formulations provided in WinSRFR.

3.2.1. MK-PIVB implementation

The MK-PIVB method matches the infiltrated volume V_Z, calculated from a post-irrigation volume balance (when surface volume $V_Y = 0$), with the integral of $z(x)$, the infiltrated depth as a function of distance x:

$$V_Z = V_Q - V_{RO} = \int_0^L z(x) WP\, dx \tag{15}$$

In Eq. (15), V_Q and V_{RO} are the applied and runoff volume, respectively, and WP is as previously defined. For a given choice of infiltration formula, $z(x)$ can be determined if the opportunity time τ is known as a function of x. If advance and recession times are measured at discrete points $i = 0 \ldots N$ along the field (t_{xi} and t_{Ri}, respectively), then the right-hand side of Eq. (15) can be calculated numerically, using trapezoidal integration

$$V_Z = \sum_{i=1}^{N} WP \frac{z_i + z_{i-1}}{2} \cdot (x_i - x_{i-1}) \tag{16}$$

where z is given by

$$z_i = k(t_{xi} - t_{Ri})^a + b(t_{xi} - t_{Ri}) + c \tag{17}$$

This expression applies when calculating infiltration with the NRCS, Kostiakov, and Modified Kostiakov infiltration functions (with b and/or c set to zero for the first two).

The objective is to solve for the parameters of the infiltration function, but with one equation, only one unknown parameter can be determined. Eq. (16) can be easily solved with the help of the NRCS infiltration families because the parameters are published values, unique to each family. Such solution involves conducting a search for that family that will most closely satisfy Eq. (16). Because the original families are discrete, the volume balance cannot be satisfied exactly. Valiantzas et al. (2001) developed a regression fit to the NRCS-family parameter values which in principle can be used to find a more precise fit, in between families. This was not adopted in WinSRFR in order to avoid confusion among users familiar with the traditional families. The Time-Rated families can also be used to solve the volume-balance problem. Since the exponent a is a function of τ_{100} (Eq. (5)), k also depends on τ_{100} through Eq. (2). Substituting these expressions into Eq. (16) sets up a non-linear equation with a single unknown, τ_{100}, which is solved rapidly with bisection (since in Eq. (5) τ_{100} lies within a defined range, $0.5 \leq \tau_{100} \leq 30$ h).

If the Modified Kostiakov (or Kostiakov) equation is adopted to describe z, then a solution for k can be developed from Eq. (16) if a, b, and c are given:

$$k = \frac{(V_Z/WP) - \sum_{i=1}^{N} (b\overline{\tau_i} + c) \cdot \Delta x_i}{\sum_{i=1}^{N} \overline{\tau_i^a}} \tag{18}$$

Here $\overline{\tau_i} = (\tau_i + \tau_{i-1})/2$ and $\overline{\tau_i^a} = (\tau^a + \tau^a)/2$.

In the original MK-PIVB method, based on the Kostiakov infiltration equation, the exponent a is determined from ring infiltrometer tests. In the absence of such measurements, a series of solutions can be generated based on different values of a. In general, several of these solutions will match the observed and simulated advance and recession times (and runoff, for open-ended systems) with reasonable accuracy, and will generate a comparable final infiltration profile (Bautista et al., in press-a). These solutions then can be used to define a range of potential infiltration conditions for subsequent sensitivity analyses.

The Modified Kostiakov equation provides more flexibility in fitting the data, but then the user has to make reasonable guesses for a, b, and c. Prior knowledge of the soil properties and experience can be used in selecting values for these parameters. Similar to the problem described above, several combinations of parameter values will simulate the observed irrigation event with comparable accuracy and these combinations can be used to define a range of potential infiltration conditions for subsequent analyses.

The solution of Eq. (16) with infiltration given by the Branch function requires an iterative application of the above-described procedure because the branch time τ_b is unknown but depends on the to-be determined value of k, through the relationship:

$$\frac{dz}{dt} = ka\tau_b^{a-1} = b \tag{19}$$

Calculations compare, first, each calculated $\bar{\tau}_i$ against a current estimate of τ_b. For the first iteration, the largest measured opportunity time is used as an estimate of τ_b. If $\bar{\tau}_i < \tau_b$, then the linear term does not contribute to infiltration; otherwise, the contribution from the non-linear term becomes constant. After calculating k with Eq. (18) (with a, b and c given), Eq. (19) is used to solve for τ_b. This new estimate of τ_b is the starting value for the next iteration. Only a few iterations are required before getting a stable value of τ_b.

The solution procedures described above apply to borders, basins and furrows, but noting that with furrows the solution will also depend on the approach used to model the wetted-perimeter effect. At this time, WinSRFR generates furrow spacing-based solutions whenever it is estimating parameters for the Kostiakov, Modified Kostiakov, or Branch functions. A future release will allow users to generate estimates based on a representative upstream wetted perimeter. When solving for the NRCS families, Eqs. (3) and (10) are used instead, while Eqs. (1), (4), (13), and Strelkoff and Clemmens' (2000) wetted perimeter formulae are used when solving for the Time-Rated families.

3.2.2. Implementation of the two-point method

The two-point method has been extensively discussed in several publications (Izadi et al., 1988; Hanson et al., 1993; Serralheiro, 1995; Bautista et al., in press-b). Three modifications have been incorporated in WinSRFR relative to the equations originally presented by Elliott and Walker (1982). First, the calculations use the average discharge calculated up to the advance times of the two selected advance points (typically midfield and end of field), instead of the average inflow rate during the entire irrigation. Gillies et al. (2007) have shown that ignoring inflow variations with volume-balance based estimation procedures compromises the accuracy of results. Second, calculations of upstream depth are based on Eq. (13). The original method assumed normal depth upstream and can lead to significant errors in the estimated surface volume with small slopes. The problem is further magnified if the surface volume is a significant portion of the total applied volume at the advance times used in the estimation (Strelkoff et al., 2003; Bautista et al., in press-b). Estimates of b based on inflow minus outflow often overestimate the steady infiltration rate and can lead to anomalous results for the k and a parameters (Strelkoff and Clemmens, 2007). Hence, the third enhancement in WinSRFR allows users to easily change b, to force k and a to reasonable values. As with the MK-PIVB calculations for the modified Kostiakov function, two-point method solutions ignore the dependency of infiltration on actual wetted perimeter (i.e., are based on furrow spacing). If a measured outflow hydrograph is available (for open-ended fields) or recession can be reasonably estimated (with closed-end fields), Bautista et al. (in press-b) have shown that better infiltration estimates can be obtained by posing a third volume balance equation. Such an approach is planned for a future release.

3.2.3. Verification of parameter estimates

Following an application of either the MK-PIVB or two-point method, WinSRFR conducts an unsteady simulation using the estimated infiltration function. The results are summarized graphically and statistically for the user. This allows the user to easily change the behavior of the estimated function, by modifying one or more parameters. For example, if the predicted runoff is larger than measured, the user may chose to increase the value of *b*. The assumption here is that the user has prior knowledge of likely ranges for those parameters, from soil properties and/or experience, and will not simply use arbitrary values to improve the goodness-of-fit.

3.3. Design and operation procedures

WinSRFR version 1 incorporated the design and operation procedures of the original BORDER and BASIN programs. Those procedures were built around databases consisting of thousands of dimensionless simulation results generated with dimensionless input variables. Each simulation in the database represents a class of hydraulically related problems. The software calculates the reference variables needed to convert the dimensionless data to their customary, dimensioned form. A summary of dimensionless formulations used in surface irrigation and examples of their use is provided by Strelkoff and Clemmens (1994). This approach was adopted to avoid repeated calls to a simulation engine, given the limited personal computer power available at the time. It is reasonably accurate and computationally efficient, but because the database is *static*, it limits the analysis to the specific system types, to the specific infiltration functional forms, and to the range of dimensionless values included in the database. The procedures in the BORDER program address only graded, open-ended border strips while the BASIN program is limited to level basins. Similar tables have not been developed either for closed-end borders (basins set on a slope) or for furrows. The only infiltration formula considered in either program is the Kostiakov. And as a further consequence of the static nature of the database, some practical field conditions lie outside the range of solutions in the database.

With the faster modern computers, it is now practical to make repeated calls to a simulation engine and *dynamically* define the performance contours as a function of the design or operational variables. On the other hand, simulations – numerical solutions of the partial differential equations of mass and momentum conservation – occasionally fail, suggesting the need for procedures that are computationally more robust. An alternative strategy for generating the large number of simulation results required for design was outlined in Clemmens et al. (1998). The strategy uses a volume-balance model with estimates of surface water volume to compute advance and recession and, ultimately, the infiltrated profile and irrigation performance (Clemmens, 2007; Strelkoff and Clemmens, 2007). Those volume balance results, however, are calibrated by the results of a zero-inertia simulation. The volume-balance model and calibration procedure, as applied to open-ended furrows, are summarized next.

A volume balance applicable to the advance phase of an irrigation event (zero runoff) provides an equation of the form

$$V_Q = V_Y + V_Z = \Phi_0 \sigma_Y A_0 x_A + (\sigma_{Z1} k \tau_0^a + \sigma_{Z2} b \tau_0 + c) W x_A \qquad (20)$$

with infiltration given by the Modified Kostiakov (or Kostiakov) equation. In Eq. (20), σ_Y is a surface-water shape factor; σ_{Z1} and σ_{Z2} are subsurface-profile shape factors, associated, respectively, with the non-linear and linear terms of the Modified Kostiakov equation; A_0 is the upstream flow area; Φ_0 is a calibration parameter of the design procedures, to be described later; τ_0 is opportunity time at the upstream end of the field; W is the border/basin width or the furrow spacing; and the other variables are as previously defined. The expression inside parentheses represents the upstream infiltrated depth applicable over the width of the border, basin or furrow. σ_Y relates the average cross-sectional area of the surface stream to A_0 and while, in reality, it varies with hydraulic conditions and time, it is often assumed to be a constant ($\approx$0.75), which is equivalent to describing the surface profile as a power function of distance with the exponent set to 0.33 (Scaloppi et al., 1995). Expressions for σ_{Z1} and σ_{Z2}, in terms of *a* and *r*, with an assumed power-law relationship

$$x_A = p t^r \qquad (21)$$

between advance distance and time, are presented in Scaloppi et al. (1995). In Eq. (21), *t* is the time since the beginning of the irrigation, and *p* and *r* are empirical parameters, with the units of *p* consistent with those of *t* and x_A (*r* is dimensionless). Eq. (20) can be written twice, once for advance to the end of the field, and once for advance to midfield, and with Φ_0 provided as noted below, the resultant simultaneous equations can be solved for each of the corresponding advance times (Clemmens, 2007; Strelkoff and Clemmens, 2007). Eq. (21) then provides the entire advance curve.

With the advance curve in place, recession times are needed to calculate opportunity times over the furrow length and the ultimate, post-irrigation infiltration profile. The simplified volume-balance procedure in WinSRFR assumes a uniform progression of recession down the field from start, at the upstream end, to finish, as all surface water vanishes at the downstream end. The start and end points of the recession curve, $t_R(0)$ and $t_R(L)$, respectively, are calculated by assuming that the minimum depth of infiltration in the post-irrigation distribution just meets the requirement, z_{req}, at the downstream end of the furrow. Fig. 3, reproduced from Clemmens (2007), defines these calculations.

With t_L the advance time to the end of the field and τ_{req} the opportunity time for the required infiltrated depth, $t_R(L)$ is calculated as

$$t_R(L) = t_L + \tau_{req} \qquad (22)$$

while at the upstream end

$$t_R(0) = t_{co} + \Delta t_{lag} \qquad (23)$$

In Eq. (23), t_{co} is a yet to be determined cutoff time and Δt_{lag} is the time it takes for the depth of water depth at the upstream end to reduce to zero. Δt_{lag} is calculated by assuming, first, that a wedge of water of length *L*, and with cross-sectional area initially A_0 at the upstream end and zero at the downstream end, is stored as surface

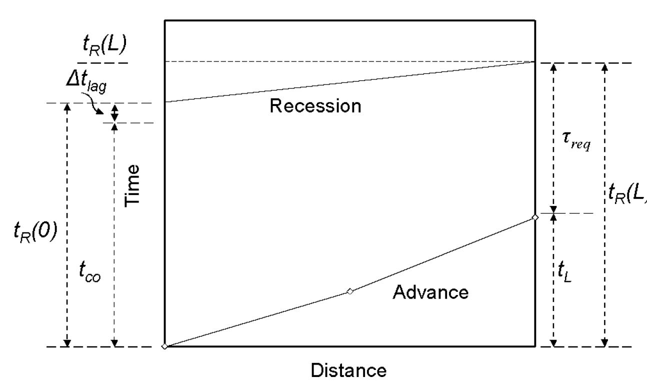

Fig. 3. Advance and recession curves and definitions for satisfying the target depth at the downstream end (Clemmens, 2007).

volume at cutoff time. This volume drains off in post-cutoff through runoff and infiltration. Calculations assume that the combined runoff and infiltration rates add up to the rate of inflow just prior to cutoff (Strelkoff, 1977),

$$\Delta t_{lag} = \Phi_2 \frac{A_0(t_{co})L}{2Q_{in}} \tag{24}$$

Here Φ_2 is a second calibration parameter. An appropriate t_{co} can be developed with a similar approximate post-cutoff expression,

$$t_{co} = t_R(L) - \Phi_1 \frac{V_Y(t_L)}{Q_{in}} \tag{25}$$

stating that in the time interval between cutoff and the end of recession, *all* the surface water originally present at cutoff drains off by infiltration and runoff at a combined rate equal to the inflow at cutoff. The surface volume at cutoff is approximated by the surface volume at the conclusion of advance [$V_Y(t_{co}) \cong V_Y(t_L)$], adjusted by a third calibration parameter Φ_1. This assumption is reasonable with steep slopes, but is less accurate with flatter slopes.

The volume-balance procedures approximate the advance and recession predictions computed with the unsteady zero-inertia model of the Simulation World. Results differ because of differences in the surface storage included in the advance calculations [which are calculated assuming normal depth in version 2.1 and with Eq. (12) in version 3.1]; differences in the t_{co} required to meet z_{req} at the end of the field; and differences in the final infiltrated volume V_Z, resulting from the assumption of linear recession. The parameters Φ_0, Φ_1, and Φ_2 adjust the volume balance results to match the zero-inertia results at a calibration point. These parameters are then applied to other points in the solution region. Φ_0 is used to match t_L. The parameter Φ_1 adjusts t_{co} to match downstream infiltrated depth (which ultimately must be equal to z_{req}). Finally, Δt_{lag} is adjusted by modifying Φ_2 to match the final infiltration volume. These adjustments are interdependent and performed sequentially (Φ_0, Φ_1, and Φ_2) and iteratively until finding constant values for all calibration parameters. When dealing with Operations Analysis, WinSRFR selects a point midway in the range of the decision variables (flow rate and cutoff time) as the initial calibration point. This selection can be modified by the user if the computations run into difficulties. In Design Analysis, the initial calibration point is located at the upper end of the length range and midway through the width range. This setup seems to give a reasonable compromise in the overall accuracy of the contour plot (Clemmens et al., 1998). Fig. 4 provides an example of the potential application efficiency contours generated by the Physical Design World, and also displays the selected calibration

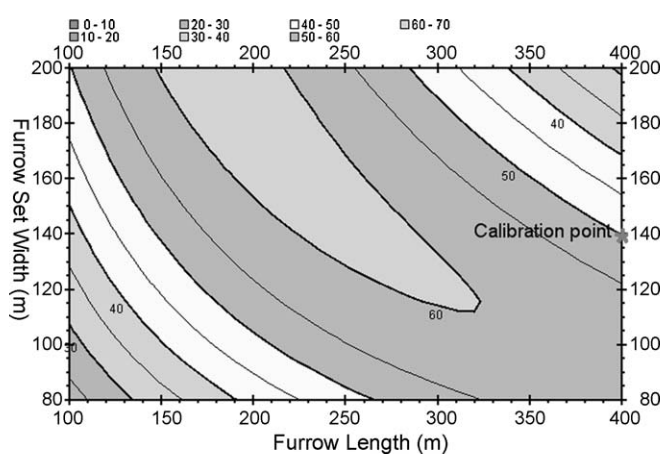

Fig. 4. Example of WinSRFR potential application efficiency contours and calibration point used to generate the contours.

point for the example. In a typical analysis, the user first specifies a relatively broad range for the decision variables, to gain an overview of system behavior. Once a potential solution region is identified, the user can reduce the range of decision variables. Then, the calibration will be more representative of the solution region and contours more accurate. Errors can also be reduced by adjusting the location of the calibration point. The user can check the adequacy of the tuning point by selecting a solution point in a region of interest. WinSRFR will perform an unsteady-flow simulation at that solution point and compare those results with the volume balance calculations. If results are not satisfactory, the contour plot can be reconstructed with a tuning point that is closer to the region of interest.

While version 2.1 continued to use the border and level basin design procedures implemented in the BASIN and BORDER programs, version 3.1, replaced them with volume balance calculations similar to the ones described above. In addition, the software now handles closed-ended furrows and borders, graded and level systems, and furrows with cutback. The procedures employed with each type of system differ in the assumptions made to calculate cutoff and initial recession times, and therefore use modified versions of Eqs. (24) and (25). More details on these procedures are found in Clemmens (2007) and Strelkoff and Clemmens (2007).

4. Ongoing and future development

Procedures are being developed to model irrigation-induced sediment (available in version 3.1) and chemical constituent transport by the irrigation stream. The WinSRFR project aims to upgrade the code of legacy applications to modern programming standards and provide a better foundation for future software development. The SRFR engine, which is at the core of WinSRFR, was initially programmed in 1980s FORTRAN 77. As such, it does not take advantage of modern programming concepts, particularly object-oriented programming. Upgrading this code will require significant effort and time. A critical area of improvements is in the computation of infiltration, particular for furrows. At this time, the plan is to add the Green-Ampt model to the list of infiltration options, but improvements to the empirical formulations will likely be investigated as well. In the longer term, many irrigation-hydraulics problems of practical interest are two-dimensional, and efforts to develop user-friendly two-dimensional modeling capabilities are underway. Current two-dimensional models are useful for research purposes, but not robust enough for practical analyses. Over time, the plan is for the software to incorporate additional concepts and software tools developed by USDA-ARS researchers and others, or to provide interfaces to those tools.

5. Conclusions

An integrated software package has been developed for hydraulic analysis of surface irrigation systems. With the software, known as WinSRFR, users can analyze the performance irrigation events and estimate field-average infiltration parameters based on field-measured data, formulate design and operational alternatives, and conduct simulation studies using an unsteady one-dimensional flow model. Because of the needed integration among functionalities, the WinSRFR development project has led to enhancements and modifications to existing parameter estimation, and design and operations analysis procedures. WinSRFR is mainly a practical tool, but will also serve as foundation for future development of hydraulic modeling and analysis techniques for surface irrigation. The software is available for public download from the USDA-ARS website http://www.ars.usda.gov/services/software/software.htm.

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